Challenges in delivering climate change policy through land use targets for afforestation and peatland restoration

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Challenges in Delivering Climate Change Policy through Land Use Targets for Afforestation and Peatland Restoration

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Abstract: Climate change policy for the land sector is challenged by complex biophysical and socioeconomic contexts. A target approach utilising land-use change indicators is often used to quantify and communicate progress, based upon assumed greenhouse gas emission (GHG) reductions. This paper investigated areal targets for woodland expansion and peatland restoration, both of which can deliver substantial carbon sequestration benefits, with uptake typically supported by grant incentives. A case study used empirical data to investigate realisation of such targets in Scotland referenced against ambitious policy commitments (net-zero emissions by 2045). Analysis of actual locations for recent afforestation and peatland restoration, referenced against biophysical data, showed that new woodland primarily occurred on land that was marginal for agriculture, usually on wetter uncultivated semi-natural land, often on organic soils. This acts to constrain net carbon gains. Both peatland restoration and new woodland show tendency to aggregate in specific zones or locations, regardless of biophysical opportunities, highlighting underlying socioeconomic factors. Differential patterns of uptake are also shown by grant applications across different land use groups. Socioeconomic factors act against more ubiquitous uptake of incentive schemes, especially for new woodland on improved agricultural land, which will constrain long-term decarbonisation objectives unless tackled directly. Investigation therefore shows that use of simple targets (e.g. trees planted) as headline progress indicators can be misleading, potentially contributing to policy failure and misuse of carbon offsets. A more spatially targeted approach is required to maximise GHG reductions relative to local contexts. Recommendations are made for improved measures that recognise spatial and temporal variability, as exemplified by certification schemes.

Keywords: afforestation; peatland restoration; indicators; climate change; carbon sequestration; Scotland

Highlights

- Climate change policy targets are compared with empirical land use changes for afforestation and peatland restoration
- New woodland in Scotland shown to occur mainly on land marginal for agriculture and uncultivated areas
- Peatland restoration tends to cluster in some locations and not others
- Socioeconomic factors explaining afforestation and peatland restoration are explored
- Limitations of using simple symbolic targets for land use change are questioned in the context of spatial and temporal variations in GHG emissions

Challenges in Delivering Climate Change Policy through Land Use Targets for Afforestation and Peatland Restoration

1. Introduction

1.1 Land Use and Climate Change

Climate change is an increasing priority for the land sector, with innovative policies required to reduce greenhouse gas (GHG) emissions and manage unavoidable climate risks (IPCC, 2019a). Within this agenda, afforestation has been recognised as a key intervention, usually to redress substantial losses from historic deforestation (Grassi et al., 2017). In developed countries, agricultural advances on better quality farmlands have been suggested to leave other land available for afforestation (Kauppi et al., 2018). Similarly, increased attention is being directed at restoration of degraded peatlands that have been functionally compromised due to past land change (Leifeld and Menichetti, 2018).

Both afforestation and peatland restoration have potential to store and sequester large amounts of carbon, hence contributing 'natural solutions' to climate mitigation policies (Griscom et al., 2017). Natural carbon sinks can offset other GHG sources, including from agriculture, thereby contributing to net GHG reductions as defined by national contributions to international agreements (Grassi et al., 2017). Furthermore, afforestation and peatland restoration can deliver many other benefits: flood and erosion alleviation; improving water and soil quality; enhancing biodiversity and landscape amenity; and providing timber and other fibres (e.g. Lin et al., 2013; Byg et al., 2017). These ecosystem services are likely to become increasingly important for climate adaptation policies (Brown, 2018). Nevertheless, despite recognised advantages from proactive intervention in the land sector, inertia and time lags counteract expeditious implementation of climate policy (Turner et al., 2018; Brown et al., 2019).

The objective of the present study was a realistic progress check on climate change policy targets by investigating empirical land use change data for afforestation and peatland restoration. Scotland (Figure 1) was used as case study because of recent policy recognition of a 'Climate Emergency' and commitment to deliver net-zero GHG emissions by 2045 based upon scientific evidence (Scottish Government, 2019). Similar commitments towards transformative decarbonisation are now being developed by many other countries: declaration of a 'Climate Emergency' being used to signify urgency of transformation required across all policy sectors.

A fundamental challenge for the land sector is converting policy aspiration into realisable targets and pathways to decarbonisation, in conjunction with other land-use objectives (IPCC, 2019a). A target-based approach is already established for defining afforestation goals. The UN Strategic Plan for Forests 2017-2030 has a goal to increase global forest area as a proportion of total land area by 3% consistent with UN Sustainable Development Goal 15, as implemented through the Trillion Tree Campaign and the Bonn Challenge which aims to globally restore 350Mha of deforested and degraded land by 2030. Individual countries have developed their own national targets consistent with these goals, despite concerns regarding their long-term feasibility (Fagan et al., 2020). Peatland restoration has more recently emerged as a priority issue, but targets are now being similarly scoped (Leifeld and Menichetti, 2018); for example, UK pathways to net-zero GHG emissions involve 55-70% restored peatland area (CCC, 2019).

Carbon offset schemes provide associated initiatives that encourage investment in afforestation or peatland projects to compensate for GHG emissions elsewhere. Growth in such schemes has, however, stimulated concerns regarding 'greenwashing', implying implementation is mainly symbolic and not robust enough to deliver timely decarbonisation (e.g. Polonsky et al., 2010; Wright and Nyberg, 2017). This concern is particularly addressed at schemes, including some 'natural solutions', that offset current GHG emissions through assumed future carbon sequestration (Baldocchi and Penuelas, 2019).

Empirical studies are therefore now needed to compare actual land use change processes with aspirational climate change indicators and targets (Turner et al., 2018; Brown et al., 2019). In general, policy indicators and targets are tools to simplify complex processes and measure progress. They are expected to be policy-relevant, quantifiable, consistent, reliable, unambiguous, transparent, and analytically robust; typically, they are time-bounded and used with appropriate instruments, such as financial grants or regulation (McCool and Stankey, 2004; Pülzl and Rametsteiner, 2009). Although an open transparent process for targets and indicators is important, it can make them political rather than scientific tools (Rametsteiner et al., 2011), whilst oversimplification can neglect underlying causality (Slee and Feliciano, 2015). Inventories provide a related policy tool, designed to standardise sampling and collation of data for reporting purposes. National GHG inventories have therefore become a key tool in reporting progress for climate change policy (IPCC, 2019b), whilst national forest inventories provide data on sustainable forestry (Tomppo et al., 2010).

The present study investigates these science-policy interactions through locational analysis of new woodland and peatland restoration schemes. Interpretation and contextualisation were used to infer underlying factors explaining scheme uptake, and hence implications for meeting climate change policy objectives as defined through indicative targets. Recommendations are then made for improved measures to evaluate and incentivise progress.

2. Policy Context

2.1 Land Use Strategy for Scotland (LUSS)

The LUSS originated in the Climate Change Act (Scotland) 2009 which defined statutory requirements for GHG reductions and climate resilience, together with recognition for an integrated approach in the land sector. Implementation has been structured through 5-year action plans (currently 2016-2021) together with review and alignment of sectoral indicator targets to guide and monitor progress (Scottish Government, 2016). Policy targets were set for 100 kha of woodland expansion for 2012-2022 (increasing to 15 kha/yr from 2024) whilst restoration of degraded peatland was set at 10 kha/yr (increasing to 40 kha/yr after 2020). These initiatives were intended to offset large GHG emissions from agriculture for which the rate of emissions reduction has slowed significantly since 2008, declining by only 0.3% since 2013, meaning the land sector is an increasing concern regarding future emissions targets (CCC, 2018).

Afforestation has become an important policy priority (Slee et al., 2014). New woodland planting reached 20-25 kha/yr in the late 1970s and early 1980s, encouraged by tax incentives, but some planting occurred on deep peat and blanket bog habitats causing major environmental damage, therefore new planting on these habitats is now proscribed (Payne et al., 2018). Afforestation rates declined to <5 kha/yr by 2010 and averaged 7.4 kha/yr in the last 5 years to 2018, with 11.2kha reported for 2018 (locational data not available yet), still higher than other UK areas (CCC, 2018). Peatland restoration is a more recent initiative: peat soils (histosols) cover more than 20% of Scotland, mainly in blanket bog habitats, but an estimated 80% of peatland is degraded (SNH, 2015) with degraded inactive bogs become carbon sources rather than sinks. Other 'peaty' soils (e.g. gleysols; podsols) with a surface organic horizon are also important carbon stores but not usually included in the core peatland resource. Restoration activities have covered ca.19kha to present (SNH, 2019).

2.2 *Opportunities and conflicts*

A large proportion of Scotland is biophysically capable of supporting woodland, although species choice is more constrained. Sing et al. (2013) investigated woodland expansion targets in the context of land availability using two sets of exclusions: (i) unsuitable biophysical land and policy commitments not to plant new woodland on peat or prime agricultural land; (ii) designated nature conservation areas and catchments with water quality acidification issues. This broad-scale analysis identified 34% of Scotland as available for new woodland, including 24% improved grassland, 11% arable, 26% unimproved grassland, and 32% montane and heath habitats.

Afforestation in Scotland involves interaction of multiple policies and plans (Muñoz-Rojas et al., 2015). Recent afforestation decline has been attributed to multiple policy aspirations converging on a 'Squeezed Middle' zone intermediate between prime agricultural lowlands and constrained uncultivated uplands (Slee et al., 2014). Strongly varying attitudes to forestry exist, including a strong cultural divide with agriculture (Feliciano et al., 2014; Nijnik et al., 2016). New woodland on farmland can incur an opportunity cost through loss of subsidies, whilst woodland grants are often seen as unaligned to land managers' needs (Lawrence and Dandy, 2014; Slee et al., 2014). Land tenure security and divergences between public and private ownership have further reinforced differences (Muñoz-Rojas et al. 2015), shaping a 'path dependency' for afforestation to occur on marginal land (Brown et al., 2014).

Similar conflicts have occurred in peatland areas, where land managers typically prioritise stocking for seasonal hunting (mainly deer and grouse) or sheep farming above peatland condition, although conservation NGOs now have an increasing profile. Surveys suggest equivocal public attitudes to peatland areas, as represented by their traditional description as 'wastes', but these disguise complex landscape identity issues extending beyond economic land values (Byg et al., 2017).

Recent years have seen increased business interest in afforestation and peatland restoration for carbon offsetting. For example, in 2019 Shell UK announced a £5m 'carbon-neutral' initiative in Scotland to deliver 1 million trees through afforestation or regeneration to offset vehicle fuel emissions.

3. Materials and Methods

Spatial analysis of recent afforestation and peatland restoration used data from national inventories referenced against biophysical and land use data. Cross-referencing was used to infer explanatory factors that could explain distribution of afforestation and peatland restoration at national scale. For afforestation, it may be expected that, other factors being equal, there would be a relatively even distribution of new woodland in Scotland across suitable biophysical areas and land cover types (section 2.2). Similarly, for peatland restoration to be relatively evenly distributed across the peatland area, especially as most is considered in degraded condition. QGIS (2019) was used for data preparation and analytical routines.

3.1 Deriving new woodland data

GIS data for new woodland planting were available from the National Forestry Inventory (NFI) for Scotland, incorporating years 2010 to 2017 inclusive (Forest Research, 2019). NFI categorical data provide annual information on woodland stocks, derived from 1:25000 air photos and refined based upon other data sources. Woodland represents stands of trees of minimum 0.5ha area (minimum width 20m) with tree crown cover >20%, (or potential to achieve that, hence including young trees). Focus here on new woodland meant areas of mature woodland were excluded, but allocated areas not yet showing tree cover were included. The area of analysis therefore included the NFI 'young trees' category and two additional categories: (i) 'ground prepared for planting' areas identified from remote sensing but as yet no trees are detected; (ii) 'assumed woodland' based upon woodland grant areas but where trees may not be planted or ground prepared. These aggregated categories defined a combined new woodland' area allocated since 2010.

NFI data also provided boundaries of the Forest and Land Scotland (FLS) estate (freehold or leasehold-type) to distinguish FLS/non-FLS woodlands during analysis. FLS is a public body (formerly Forestry Commission Scotland) responsible for forest-related services. Non-FLS woodland is assumed to be mainly privately managed, including estates, farm holdings or forest businesses, but also NGOs.

3.2 Deriving peatland restoration data

Peatland Action provided data on grant-aided restoration activities 2012-2017 (SNH, 2019). In a few cases, grants were allocated to multiple sites within a small area, counted here as one site. Restoration site boundaries were defined from site investigation data and may exclude other small areas.

3.3 Reference geodata (biophysical and land cover)

These data provided information on local biophysical conditions influencing land use options and on pre-existing land cover before change. Climate metrics indicated relative warmth and wetness which have a strong influence on plant growth and potential land cover/use, including factors such as moisture availability which may also influence organic decomposition and soil type. High-resolution data were available at 25m resolution from an updated bioclimate zonation of Scotland derived using geographically-weighted regression and interpolation of bioclimate parameters (Brown, 2017a). Classes defining thermal zonation (annual accumulated growing degree days above 5^{o}C adjusted for wind exposure) and moisture balance zonation (April-September balance of precipitation against potential evapotranspiration) were utilised to represent warmth and wetness factors, based upon 1991-2010 long-term averages.

Soil data also identified potential land cover/use, including parameters such as soil depth, texture, structure, drainage and nutrient availability. For the present study, differentiation between mineral and organic soil classes was of most interest, as provided by the national Carbon and Peatland Map derived from 1:250000 soil mapping validated against habitat data (Scotland's Soils, 2018). This schema classifies organic soils into 3 classes according to decreasing carbon content: (i) dominantly peat soils (histosols) with a thick surface organic horizon >50cm; (ii) dominantly peaty soils with a less thick organic horizon but also containing some peat; (iii) other organic soils not containing peat and with a lower overall carbon content. Two further classes are defined: (iv) organo-mineral soils, intermediate in carbon content between organic and mineral soils; (v) mineral soils, which have limited organic material and lower carbon content. At national scale, the 'core peatland' area (ca. 1860kha) is based upon soil classes (i) and (ii); uncertainties inherent in this coarse-scale data are then refined by site investigation for restoration activities.

General data on woodland suitability was obtained from the Land Capability for Forestry (LCF) classification for Scotland (1:250000 scale) that integrates climate, soil and topography constraints (Bibby et al., 1988; Supplemental Material). LCF identified land flexibility for different types of productive tree crops based upon 7 summary classes: Excellent (F1); Very Good (F2); Good (F3); Moderate (F4); Limited (F5); Very Limited (F6); Unsuitable (F7). Classes F4/F5/F6 become increasingly constrained to hardier species, predominantly conifer but also birch. More detailed analysis of combined soil-climate limitations then utilised Soil Wetness classification, this acting as a major land use constraint in Scotland (Brown, 2017b). These data categorise land quality into 6 wetness classes, based upon both intrinsic soil drainage properties (notably depth to a slowly permeable layer that inhibits drainage) and climate wetness (proportion of year when precipitation exceeds potential evapotranspiration, indicating soil at field capacity). Soil wetness classes therefore range from free-draining Class I to very wet Class VI that usually remains waterlogged throughout the year. Soil wetness class data had been adjusted for areas with artificial field drains (Brown, 2017b), with particular relevance for poorly-drained gley soils (gleysols) which have commonly been drained in Scotland to provide improved agricultural land, typically improving intrinsic constraints by 2 wetness classes (e.g. from V to III) depending on local climate. Characterising artificial drainage areas remains a major uncertainty for land evaluation in Scotland (Brown, 2017b).

Data to identify pre-existing land cover were obtained from the Land Cover Map of Great Britain 2007 (LCM2007) (Morton et al., 2007), reclassified into broad categories (arable; improved grassland; semi-natural grassland; mountain, heath and bog; other) based upon dominant land cover at 25m resolution. In addition, as topography can also influence land use decisions, slope data were derived from Ordnance Survey Terrain50 dataset (50m resolution).

Reference was also made to large-scale peatland degradation areas, as derived from the Land Cover of Scotland 1988 air-photo classification (Macaulay Institute, 1993) based upon 'blanket bog/peatland vegetation with erosion' as dominant features. LCS88 provided the most recent national-scale data for peatland condition and this attribute remains an important source of uncertainty. Smaller-scale localised degradation in also common, but this requires site-level investigation.

3.4 Analysis of spatial correspondence

Spatial correspondence between new woodland and reference biophysical datasets was investigated using QGIS intersect functions, with correspondence areas totalled at national scale, also distinguishing categories for FLS/non-FLS land. A similar operation was applied for peatland restoration data; in this case only referencing topographic and land cover data because restoration areas remain relatively small at present.

4. Results

Most new woodland (83%) in Scotland was identified as occurring on non-FLS land. New woodland was associated with LCF suitability classes as follows: 8% Excellent/Very good/Good; 14% Moderate; 24% Limited; 36% Very Limited; 18% Unsuitable. The broad scale of LCF mapping implies some likely misclassification, notably 'Unsuitable' areas being locally suitable. However, the general correspondence can be considered robust, most new planting occurring on land with limited flexibility regarding tree species (i.e. predominantly conifers); both FLS and non-FLS owned land followed the same pattern. Analysis of new woodland area against slope (Figure 2a) showed the most common association was with gentler slopes <10°, but a significant proportion corresponding with steeper slopes, although with very little on the steepest slopes (>25°). Analysis showed no major slope differences between FLS and non-FLS land.

Comparing new woodland against soil classes (Figure 2b), about equal proportions correspond with mineral (45%) and organic soils (47%), with smaller amounts on intermediate organo-mineral soils (8%). On organic soils, ca.20% of the new woodland is on the higher carbon-rich classes consisting of dominantly peat or peat/peaty soils. A distinction is evident between FLS and non-FLS land, with the former disproportionately associated with the intermediate 'carbon-rich organic soils 'class, whilst the latter have proportionately greater association either with mineral soils or with the peat and peat/peaty classes.

Comparison of new woodland against climatic warmth (Figure 2c) shows the majority (almost 80%) associated with the two warmest thermal classes (T1 and B3), a rather smaller proportion with the intermediate class (B2), and very little on the colder classes where tree growth becomes severely restricted. Again, FLS planting seems more commonly associated with an intermediate class (B3 here).

Analysis for climatic moisture (Figure 2d) suggests a bimodal distribution with new woodland predominantly associated either with the wettest climate (P) or a climate that is only moderately wet (H3). It also evident that new woodland on FLS land is more skewed towards occurring on the extremely wet (P) class with excessive precipitation. Further investigation through correspondence with soil wetness classes (Figure 2e) again shows a bimodal distribution: although a significant proportion of new woodland occurred on free-draining class I land (20%), the vast majority corresponds with classes at the opposite (wetter) end of the spectrum, especially on class VI representing almost permanently waterlogged land. As with climatic wetness (Figure 2d), FLS new woodland is skewed to occur predominantly on wetter soils. For reference, improved agriculture is primarily based on drier (class I-IV) soils (Brown, 2017b).

Regarding land cover replaced by new woodland, some (ca.16%) was considered susceptible to LCM2007 misclassification through correspondence to built areas or existing woodland, and therefore excluded. Analysis of remaining correspondences (Figure 2f) showed a large majority (85%) was previously unimproved semi-natural land, either rough grassland or mountain/moor/bog category. By contrast, only a small new woodland area replaced improved grassland and a very small area replaced arable. Although FLS/non-FLS new woodland has general ratio 0.2, rather higher FLS proportions occurred for mountain/moor/bog (0.27) and improved grassland (0.29) compared to rough grassland (0.22) and arable (0.13).

Comparison of peatland restoration sites with core peatland areas (Figure 3) showed an uneven distribution. Distinct clusters are evident, particularly in the Central Lowlands and Southern Uplands with smaller clusters in the eastern Highlands and NE Scotland, Sutherland/Caithness, and the Northern Isles. By contrast, very few sites were identified in the western Highlands and none for the Western Isles despite extensive degraded peat. Altitudinal analysis of restoration sites (Figure 4) shows greater proportional preference at lowest elevations (<200m) compared to general peatland distribution, which may be attributed to accessibility and its impact on restoration costs. However, a small proportional preference for restoration at higher altitude (>600m) also seems apparent, associated with montane biodiversity value. Comparison of restoration sites against land cover classes shows that, as may be expected, areas are predominantly mountain/moor/bog or semi-natural grassland. Nevertheless, a small restoration area (ca. 20%) corresponded to previously forested land, highlighting overlapping zones for peatland restoration and woodland expansion.

5. Discussion

5.1 Factors influencing afforestation and peatland restoration

Analysis has shown new woodland and peatland restoration in Scotland has an uneven distribution compared to biophysical factor opportunities. Afforestation has occurred predominantly on wetter soils (Figure 2e) that are often organic rather than mineral (Figure 2b) indicative of marginal locations for agriculture. Peatland restoration has tended to cluster in specific locations whilst other regions with extensive peatland have seen very limited uptake (Figure 3). These findings point towards underlying socioeconomic factors. New woodland has not occurred to any great extent on improved agricultural land (Figure 2f), despite its suitability and availability of woodland grants. This may be expected for arable, with crops providing generally greater economic returns than livestock from grassland. Limited planting on improved grassland can be attributed to several factors*:* agricultural subsidies, land tenure issues, presumed irreversibility of decisions, high initial costs, and cultural factors associated with farmers' identity (section 2.2; Slee et al., 2014; Lawrence and Dandy, 2014). Similar issues have been recognised elsewhere (McDonagh et al., 2010; Hardaker, 2018) including resistance to woodland carbon schemes (Wynne-Jones, 2013). An exception is some non-FLS woodland on reasonably good quality land (Figure 2e), attributed to commercial timber production.

In Scotland, a further legacy issue is agricultural 'land improvement', notably extensive field drain installation to reduce soil wetness, grant-supported until the 1980s to enhance farmland productivity. Despite current problems maintaining field drains in a wetter climate (Brown, 2017b), drained land is still primarily perceived as 'productive' farmland (Burton, 2004), meaning most new woodland is allocated to wetter unimproved land with limited agricultural value.

Heterogeneous distribution of new woodland and peatland restoration is also associated with different land managers awareness of scheme benefits (Whitfield et al., 2011; Lawrence and Dandy, 2014). Land manager groups can have divergent attitudes to new opportunities: hence, private estates are typically interested in new income streams to support existing activities; the forest industry is mainly interested in softwood timber production; and conservation NGOs are motivated by enhanced biodiversity value (Raum, 2018). Most new woodland occurs where constraints on farming means land managers are more open towards alternative uses (Brown et al., 2014) but typically in 'opportunistic' mode, being distant from their core values (Gasson, 1973; Duesberg et al., 2014). A woodland grant for poorer quality land becomes a rational alternative if other factors are conducive. Similar opportunism has been identified with uptake of agricultural GHG reduction schemes (Feliciano et al., 2014). Previous analysis of UK woodland grants and related schemes has shown strong annual tendency for spatial clustering, interpreted through knowledge diffusion variability as practitioners try to reconcile grant stipulations with different local contexts; early adopters tending to be mixed-use estates already with woodland (Brown et al., 2018). Traditional knowledge diffusion patterns apparently persist despite modern communications technology.

Land use in peatland areas is also severely constrained by intrinsic wetness constraints unless artificially drained, but drainage is now discouraged by policy. Hence, a peatland restoration grant may also provide a rational economic alternative, especially if past drainage was ineffective, although, in some locations, peatland is competing with forestry (Payne et al., 2018). Successful peatland restoration grant applications in Scotland (Figure 5) show dominance by NGOs and local/national government with much less uptake by private estates despite them owning most peatland.

In summary, whilst legacy issues persist for traditional land managers, opportunities appear more actively pursued by new land manager groups (notably conservation NGOs) and often clustering in particular locations. These new groups align opportunities with novel approaches to land use, usually with different perspectives regarding costs and benefits (e.g. on a not-for-profit basis) over both short- and long-term (Raum, 2018).

5.2 Implications for Climate Change Policy

As now discussed, Scotland typifies a general confusion between land systems science and climate change policy, also involving carbon offsetting and the scale of transformation required to deliver decarbonisation (Mackay et al., 2013; Turner et al., 2018). Confusion occurs because generalisations obscure considerable spatial and temporal variability in GHG emissions from different contexts (Popkin, 2019).

Firstly, predominance for new woodland on wetter uncultivated land in Scotland limits carbon gains within the 25-year timeframe to reach net-zero emissions. Uncultivated land already has substantial carbon stocks, especially on organic soils that, when in good (undrained) condition, provide significant carbon sequestration (Ostle et al., 2009). New woodland planting using fast-growing non-native species, most commonly Sitka spruce *(Picea sitchensis* (Bong.) Carr.), requires improved drainage to facilitate establishment on wetter soils. Drainage and lowered water tables usually incurs significant soil carbon oxidation loss, although quantity and duration vary with soil type and management (Reynolds et al., 2007). Time to net carbon sink status can vary from 10-20 years for Sitka spruce on mineral gleys to 30+years (and into the second rotation) on organic peaty gleys that characterise much recent planting in Scotland (Black et al., 2009; Ball et al.., 2011; Vanguelova et al., 2019). Native species may require no drainage improvement for establishment but have slower growth rates, although with a wider range of benefits (notably for biodiversity), highlighting important decision trade-offs and that substantial gains accrue mainly in the longer-term (Brown et al., 2014).

Potentially larger carbon sequestration gains could be achieved through woodland on cultivated farmland but with important socioeconomic factors and trade-offs. As previously noted, woodland replacing grassland seems more realistic, although carbon gains are smaller for grassland than arable (Ostle et al., 2009). Moreover, although trees eventually sequester substantial carbon stocks, net declines in soil carbon stocks may occur from lost grassland fine-root systems, especially for conifers in wetter conditions characteristic of Scotland (Guo and Gifford, 2002; Barcena et al., 2014). Livestock numbers, fertilizer application, grass species, and mowing frequency, all affect grassland baseline GHG balances (Ward et al., 2016), but these define agricultural management intensity rather than woodland transition. GHG abatement would also likely be greater for land use change on drained organic/organo-mineral soils currently act as significant GHG sources (Paul et al., 2018).

Moreover, there are wider indirect issues to consider: excessive focus on specific outcomes can have negative consequences in land use systems (Brown et al., 2019). Loss of local farmland may instead cause agricultural produce to be displaced and imported from other countries, with implications for GHG emissions including from deforestation elsewhere. Marginal land may be considered inefficient for production, requiring more inputs per unit output and increased maintenance (e.g. drainage), but concepts of 'efficiency' are multi-facetted and debated (Garnett et al., 2015).

Peatland restoration has similar challenges. Very few sites exist for some regions with hyperoceanic wet conditions (notably western Highlands: Brown, 2017a) supporting higher carbon sequestration (cf. Yu et al., 2012; Lunt et al., 2019). The current grant system favours conservation NGOs because restoration matches their mission to enhance biodiversity, encouraging investment of resources into the application process. Although sites are screened for carbon benefits, they are not yet prioritised for ecohydrological functioning or maximal net carbon storage. Restoration requires a long-term strategy, sometimes producing unexpected effects on GHG fluxes, including initial release of methane or dissolved organic carbon (Abdalla et al., 2016; Parry et al., 2016; Hadden and Grelle, 2017). Furthermore, climate warming threatens some peatlands, notably drier areas of eastern Scotland (Ferreto et al., 2019).

5.3 *Indicators, targets, and certification*

Although Scotland is currently not delivering on afforestation and peatland restoration targets (CCC, 2018), the present study questions the role of such targets for referencing progress. A simple areal indicator has limited scientific credibility because of spatial and temporal variability in GHG emissions. A hectare of change in different contexts can contribute rather varyingly to net GHG emissions, meaning areal targets could be met but with limited contribution to net GHG balance, especially before 2050. Interventions therefore require a stronger link to expected outcomes for net GHG emission including improved data on 'what works, where, and when' (Romijn et al., 2018; Steg, 2018). This is currently complicated by large uncertainties in land sector GHG inventories due to intrinsic variability (Grassi et al., 2017).

Whilst recognising inherent challenges in GHG verification it is proposed that increased use of indicators based upon certification initiatives can facilitate further progress. Monitoring and verification aim to cross-reference management activities with data from experiments, repeat field sampling, remote sensing, and modelling to independently quantify carbon stocks and GHG fluxes (Smith et al., 2019). For example, the UK Woodland Carbon Code (initiated 2011) and UK Peatland Code (initiated 2015) both provide voluntary certification schemes to register and verify carbon sequestration, which may then be used in emissions offsets. Total certified area and associated certification data can therefore provide more robust indicators of policy progress on target outcomes. Certification data could also provide robust indicators for net GHG changes relative to different land use and biophysical contexts (e.g. tree species, soil type, climate). This could support enhanced stakeholder engagement in combination with agricultural certification, including net GHG emissions by land holding or output (Slee and Feliciano, 2015), and to better deliver spatially-targeted GHG reductions and co-benefits (e.g. Kim and Cho, 2019). Costs could be potentially covered through a certification-based quality-assurance premium for land managers or reworked grant awards that reward innovation in GHG reduction.

6. Conclusions

This paper has provided a detailed example of the scale of transformational challenge involved in decarbonising the land sector. As with several other countries, Scotland has set a highly ambitious net-zero GHG target (for 2045). However, 'one size fits all' incremental policies are constrained by land sector inertia, high variability of GHG fluxes in space and time, trade-offs with other land use functions, and the need to engage with a wide diversity of stakeholder interests. Hence, simple areal targets for woodland expansion in Scotland have so far been difficult to meet with afforestation occurring mainly on marginal land for agriculture, often on wetter organic (carbon-rich) soils. This limits net gains through carbon sequestration. Similarly, peatland restoration has tended to cluster in specific locations excluding others that seemingly offer equal or greater GHG reductions. Uneven distribution of peatland restoration and woodland expansion compared to biophysical potential factors points to socioeconomic influences, notably partial and sometimes opportunistic engagement with land managers.

Over-reliance on simple symbolic target indicators for tree planting or peatland restoration is therefore likely to be ineffective and misleading for referencing climate change policy progress. Land use change in some locations, notably plantation forestry on wet organic soils (in addition to peat) for Scotland, may be rather limited for meeting net zero GHG timescales, despite apparent convenience now. This concern extends to unvalidated use of such indicative targets in carbon offsetting schemes.

Transformation to net-zero GHGs for the land sector requires innovative science-policy-practitioner frameworks to enhance knowledge exchange on 'what works, where, and when'. Major challenges remain in developing improved transparent GHG accounting schemes and indicators that recognise complex spatial and temporal variability in carbon stocks and GHG fluxes. The case study presented here shows need for systematic monitoring collation and interpretation of data from diverse land uses, soils, climate zones, and management regimes, particularly because land use change can produce outcomes differing from initial assumptions. Certification schemes can have a key role in this knowledge exchange, whilst facilitating more transparent validation of carbon offsets for afforestation and peatland restoration.

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FIGURES

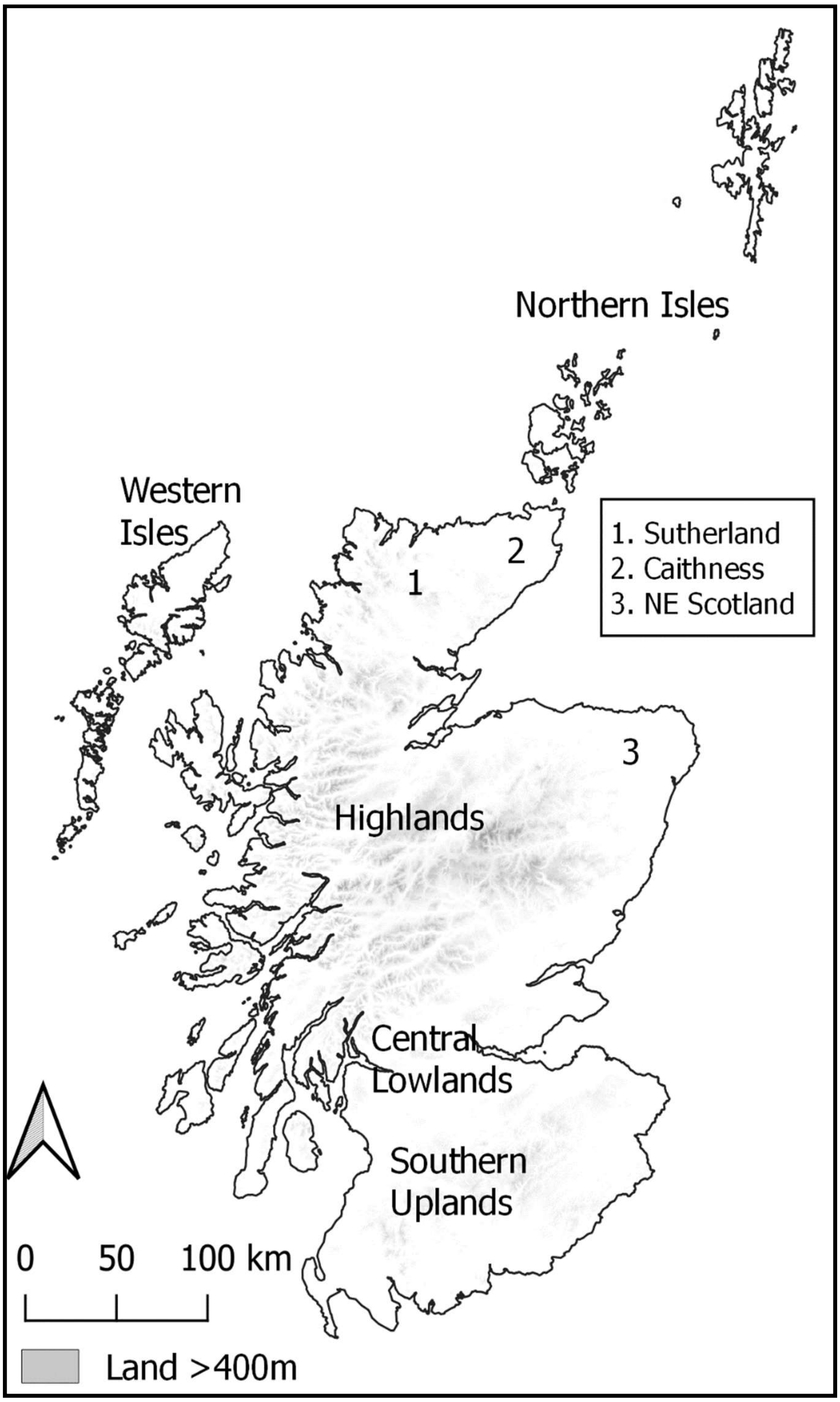
Figure 1. Scotland with geographic areas noted in text

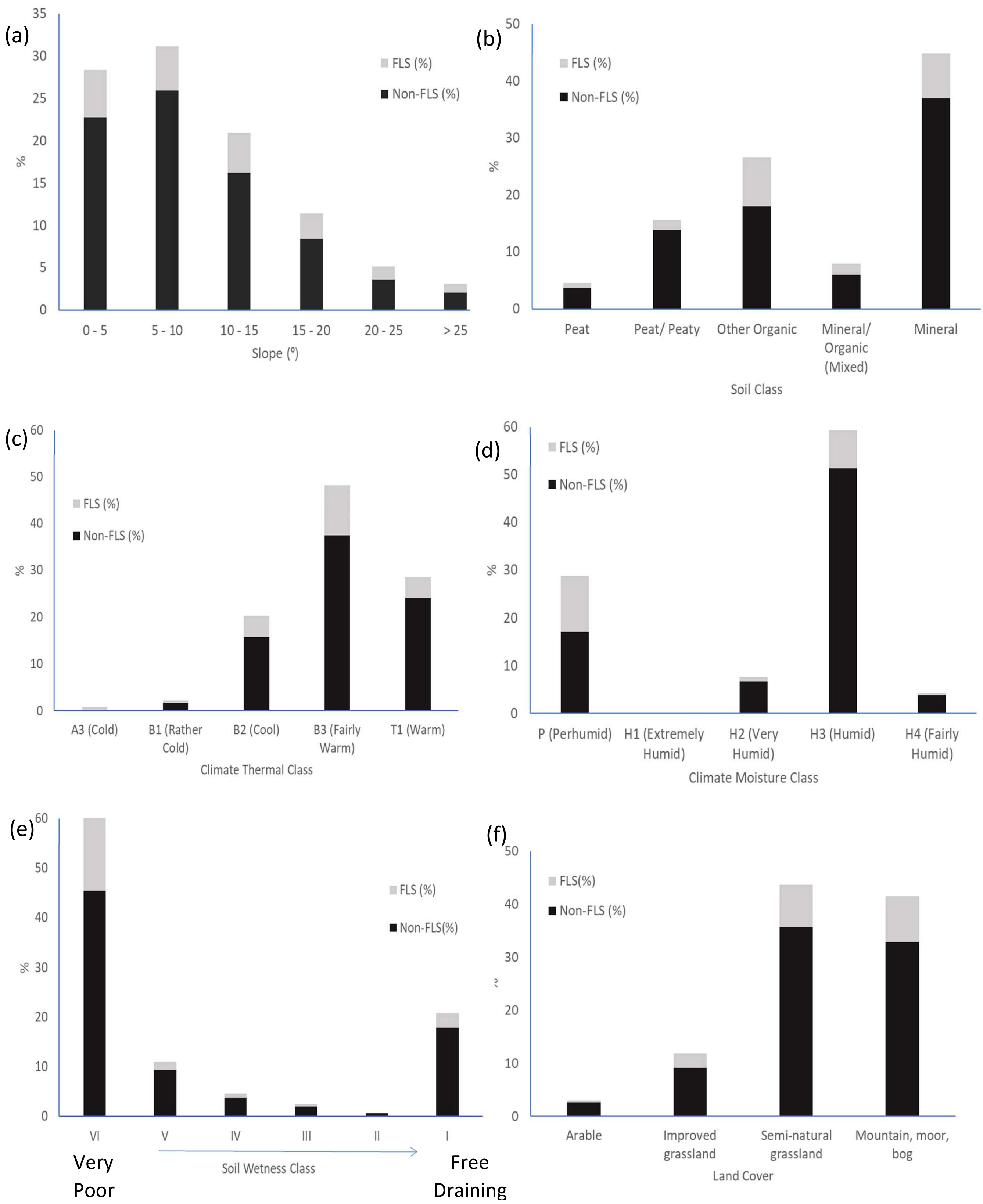
Figure 2. Analysis of new woodland (%) against: (a) slope categories; (b) soil organic/mineral classes; (c) climate thermal classes; (d) climate moisture classes; (e) soil wetness classes (I to VI, after Brown, 2017b); (f) replaced land cover types. [‘FLS’: land managed by Forest & Land Scotland; ‘non-FLS’: land managed by others]

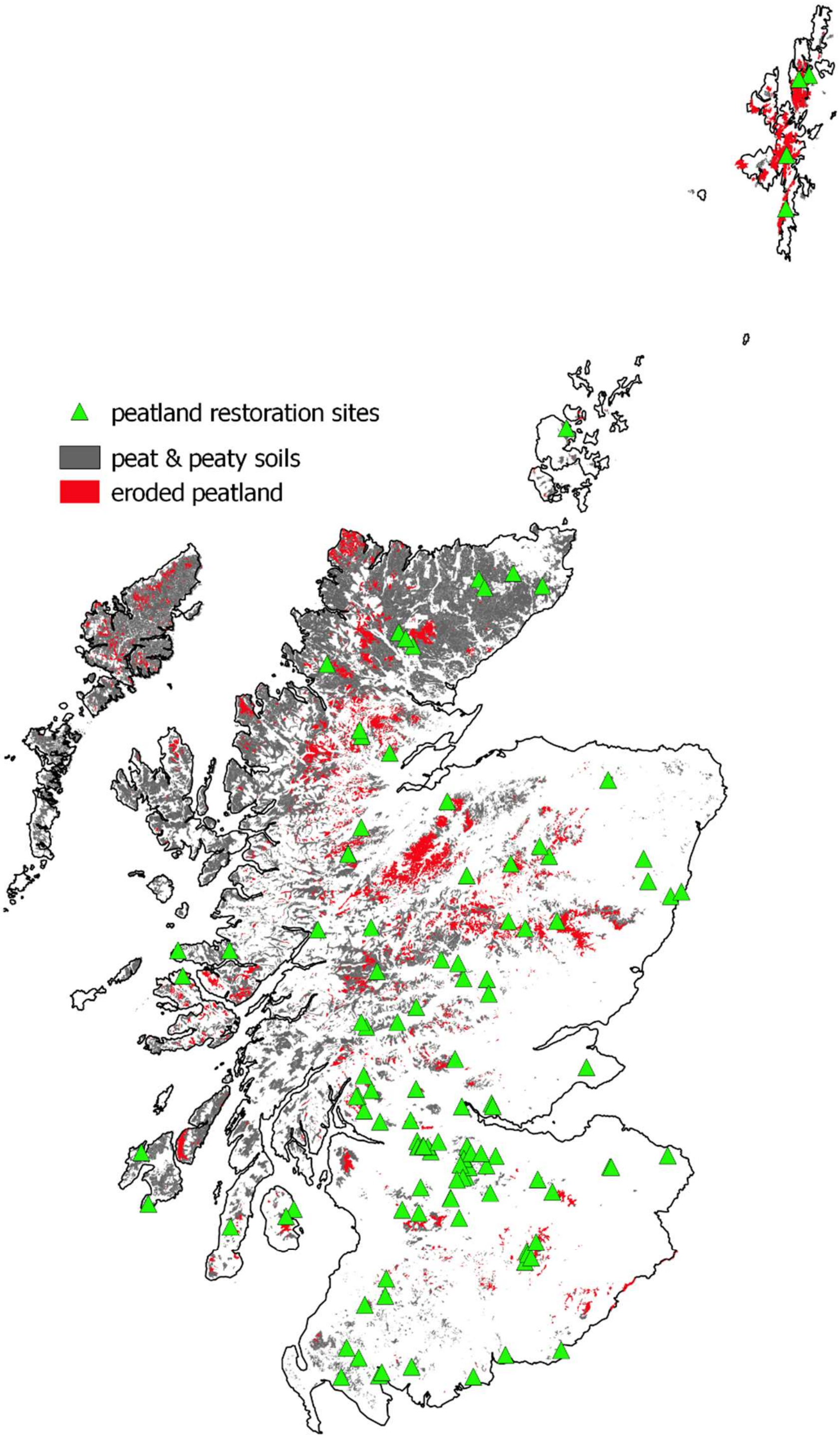
Figure 3. Location of peatland restoration sites

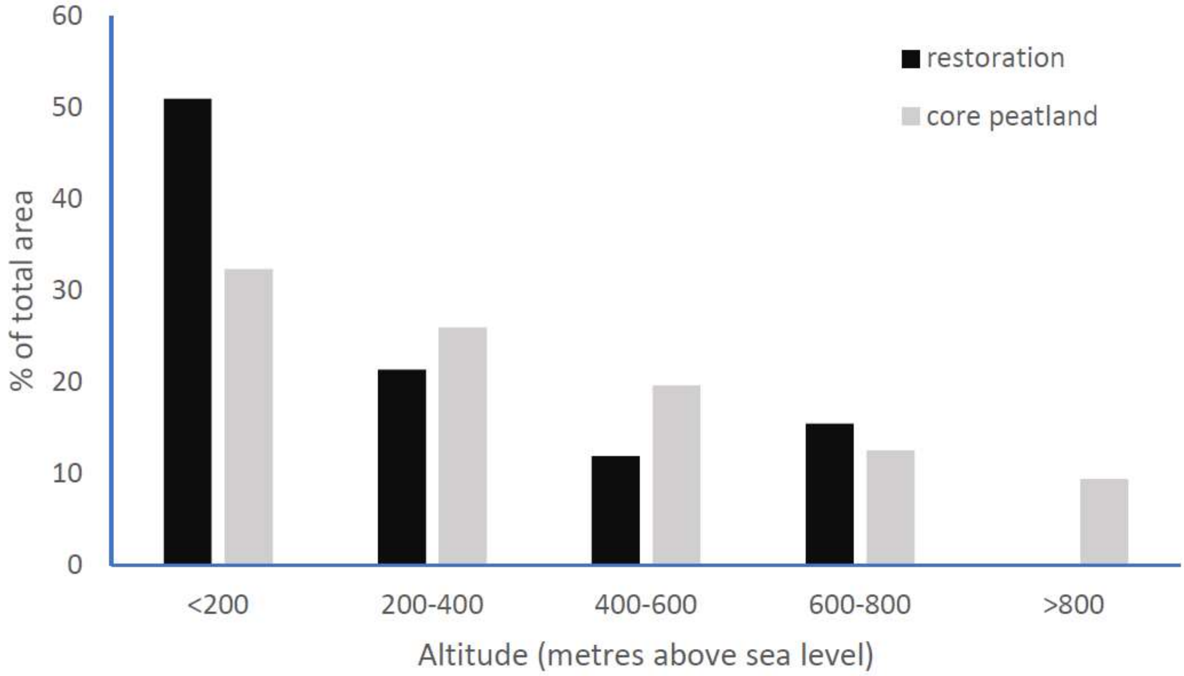
Figure 4. Altitudinal distribution of peatland restoration sites compared to core peatland area (peat and peaty soils: section 3.3)

Figure 5. Peatland restoration grants by land manager type (source: Peatland Action)

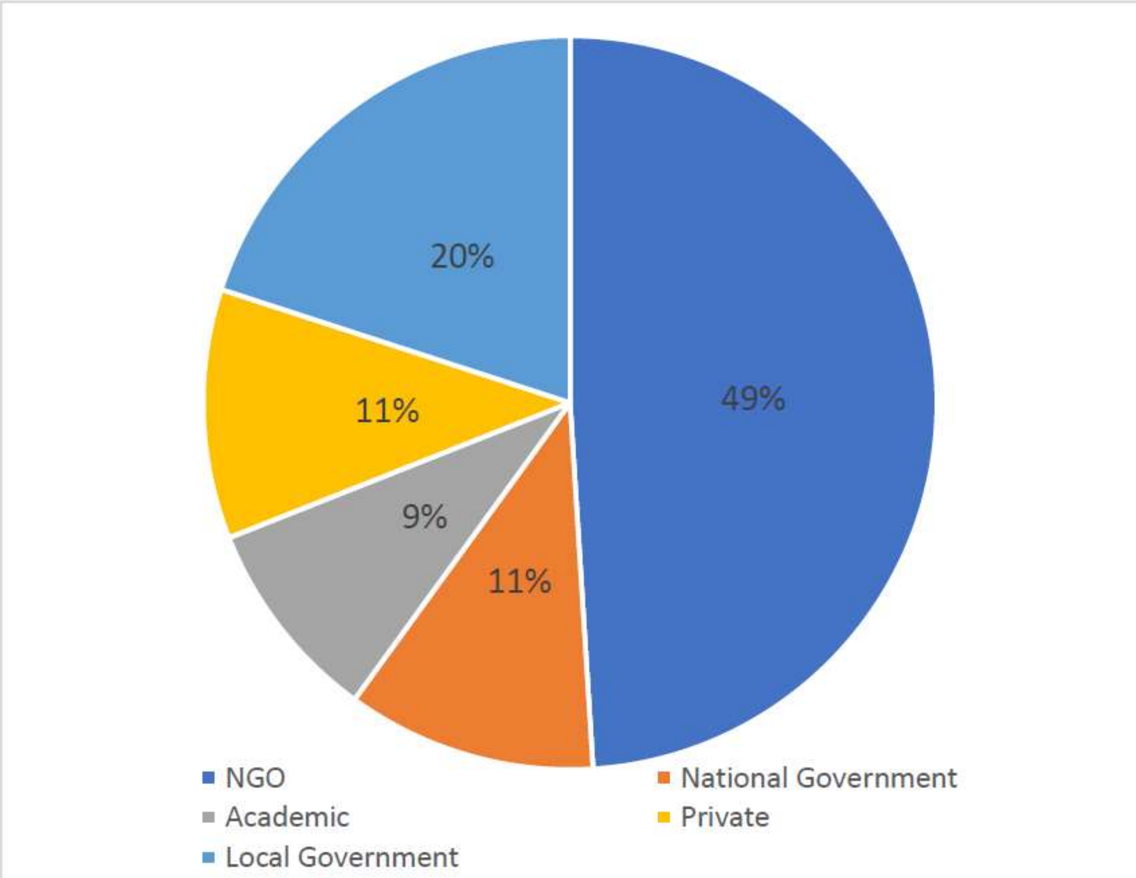

Northern Isles
Western Isles
1
2
1. Sutherland
2. Caithness
3. NE Scotland
3
Highlands
Central Lowlands
Southern Uplands
0 50 100 km
Land >400m


(a)
FLS (%)
Non-FLS (%)
%
0 - 5
5 - 10
10 - 15
15 - 20
20 - 25
> 25
Slope (°)
(b)
FLS (%)
Non-FLS (%)
%
Peat
Peat/ Peaty
Other Organic
Mineral/ Organic (Mixed)
Mineral
Soil Class
(c)
FLS (%)
Non-FLS (%)
%
A3 (Cold)
B1 (Rather Cold)
B2 (Cool)
B3 (Fairly Warm)
T1 (Warm)
Climate Thermal Class
(d)
FLS (%)
Non-FLS (%)
%
P (Perhumid)
H1 (Extremely Humid)
H2 (Very Humid)
H3 (Humid)
H4 (Fairly Humid)
Climate Moisture Class
(e)
FLS (%)
Non-FLS(%)
%
VI
V
IV
III
II
I
Very Poor
Soil Wetness Class
Free Draining
(f)
FLS(%)
Non-FLS (%)
Arable
Improved grassland
Semi-natural grassland
Mountain, moor, bog
Land Cover


peatland restoration sites
peat & peaty soils
eroded peatland



restoration
core peatland
% of total area
0
10
20
30
40
50
60
<200
200-400
400-600
600-800
>800
Altitude (metres above sea level)


20%
11%
9%
11%
49%
NGO
National Government
Academic
Private
Local Government

1

SUPPLEMENTAL MATERIAL

1. **Land Capability for Forestry classification for Scotland (after Bibby et al., 1988)**